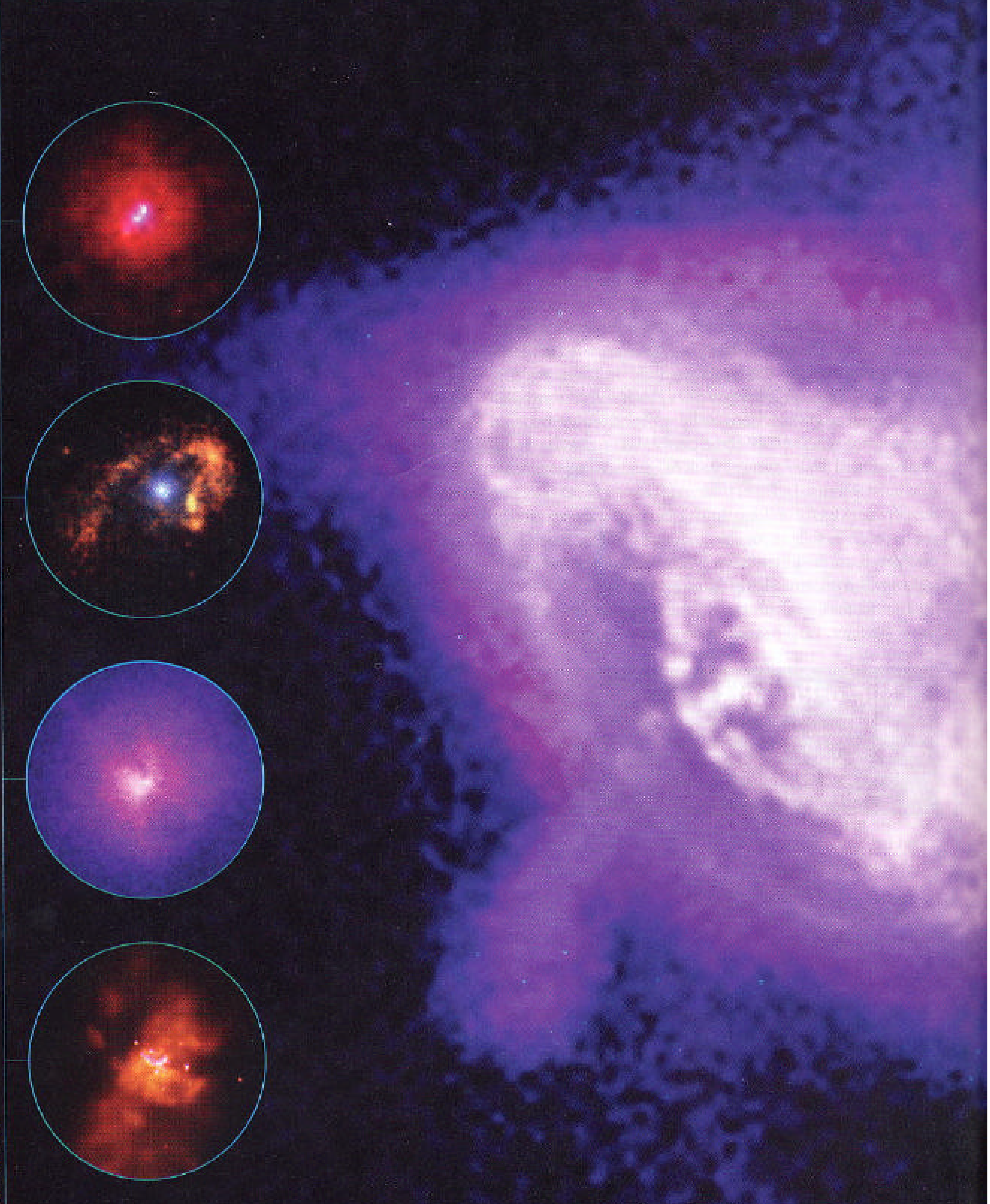


Images from the Chandra X-ray telescope are created by photons from gases heated to millions of degrees by violent explosions or enormous gravitational forces. The spiral above is the Crab Nebula. At left, from top, are a large galaxy in Bootes, a supermassive star and nebula in Carina, a cluster of galaxies in Hydra, and M82, the starburst galaxy nearest Earth.

Sensitive high-resolution charge-coupled devices inside astronomical telescopes enhance views of the universe

Seeing Stars With Digital Eyes

BY DAVID APPELL
CONTRIBUTING EDITOR

It takes a very good telescope to "see" a pit of absolute blackness. Yet in January researchers announced they had "seen" the boundary of a black hole, the infamous event horizon from which nothing ever returns.

"It is a bit odd to say we've discovered something by seeing almost nothing at all—less than the smile of the Cheshire cat, so to speak," acknowledged Michael Garcia of the Harvard-Smithsonian Center for Astrophysics, Cambridge, Mass., "but, in essence, this is what we have done."

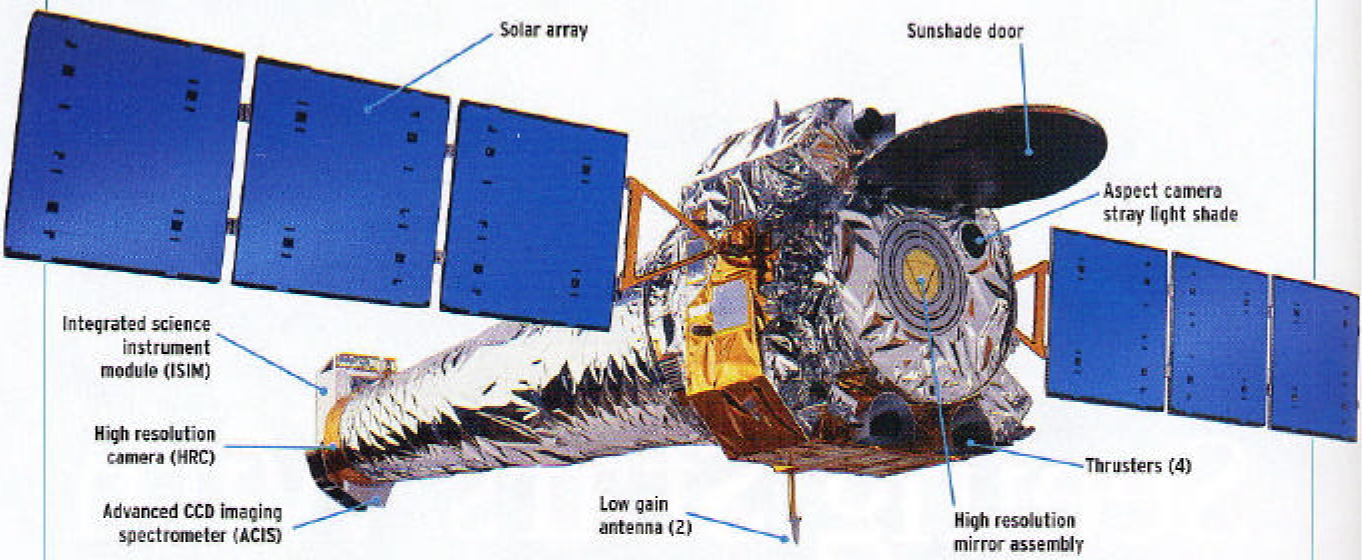
Essential to the discovery were the novel semiconductor X-ray sensors installed in a telescope aboard NASA's Orbiting Chandra X-Ray Observatory. Garcia and his colleagues used these charge-coupled devices (CCDs) to study the X-ray emissions of celestial objects [see images, left], the most intriguing of which may be the X-ray novae. Each of these objects comprises a sun-like star and a collapsed star, which could be a black hole or a neutron star. If the two stars are close enough, the gravity of the collapsed star pulls a stream of gas from its companion "sun," and a brilliant burst of X-rays erupts as the gas is heated to very high temperatures. Often, periods of intense X-ray activity are separated by long periods of dormancy, during which much less radiation is emitted.

Garcia's team found that during dormancy the energy emitted by X-ray novae with black holes is markedly different from that emitted by novae containing neutron stars: the black hole type emits only 1 percent as much energy as the neutron star type. The most straightforward explanation, according to the scientists, is that the black holes are surrounded by event horizons that suck in all the energy incident upon them. Below the event horizon, the gravitational force is so great that nothing—not even light—can escape. "One could even say that this work shows why black holes deserve to be called 'black,'" said team member Stephen Murray. The finding, presented at a meeting of the American Astronomical Society in January of this year, confirms the deduction derived from Einstein's theory of general relativity by German astronomer Karl Schwarzschild back in 1916.

CCDs are by now a mature technology, but continue to play a starring role in many areas of science, such as oceanography, biology, and high-energy physics. In astronomy, more new telescopes have recently begun detecting ever fainter objects in the depths of the universe, thanks to CCD arrays of unprecedented size.

The Chandra instrument that enabled Garcia and his colleagues to peer so nearly into the heart of

NASA, CHANDRA X-RAY OBSERVATORY CENTER, SMITHSONIAN ASTROPHYSICAL OBSERVATORY



Chandra's spacecraft system contains thrusters for positioning; antennas for communication with ground stations; solar panels for energy; and sunlight and stray-light shades to keep unwanted light out of the telescope. A high-resolution mirror assembly directs the photons to the Advanced CCD Imaging Spectrometer (ACIS) located at the instrument's focal point. A second camera, the high-resolution camera (HRC), is a microchannel plate detector for imaging X-rays below 100 eV.

darkness is called ACIS, for Advanced CCD Imaging Spectrometer [see figure above]. Since its launch in July 1999, it has been key to one discovery after another in black hole physics, supernova science, and the astronomy of some of the strangest inhabitants of the universe.

ACIS typically collects photons for up to 40 000 seconds (about 11 hours) per object. That's roughly the time needed to collect more than 100 photons, the number needed to give researchers a rough measurement of X-ray temperature, explained Garcia.

Indeed, photon collection times of up to a million seconds (over 11 days) are possible, according to Gordon P. Garmire of Pennsylvania State University, University Park, instrument principal investigator of ACIS. Beyond that length of time, background noise may become a problem.

"It's revolutionized our ability to do astronomy in X-rays," said Garmire. The spectrometer is superb both at detecting the X-ray photons incident on it and at recording each photon's energy alongside the degree of precision with which it was measured. The photon energy "gives us some idea of the character of the thing that we're looking at," Garmire explained, and precision is better than one arc-second positioning over a large field of about 10 arc minutes. "We don't guess anymore which object is the X-ray emitting object—we know," said Garmire.

A similar claim was made by Martin Weisskopf, chief project scientist for the Chandra program at NASA's Marshall Space Flight Center, in Huntsville, Ala. "Chandra has changed the way we look at the universe," he said. The scientists in charge have observed several firsts. In the Milky Way, they found a faint X-ray source that may be the long-sought X-ray emission from the super-massive black hole known to be at the galaxy's center. They were the first to witness a flare from a brown dwarf, a failed star in a category long thought to have too little mass to emit such energy. They have also found faint X-ray sources that include an abundance of active supermassive black holes, indicating that giant black holes were much more active in the past than at present.

X-ray CCDs at work

The Advanced CCD Imaging Spectrometer (ACIS) aboard Chandra is an arrangement of 10 planar 1024-by-1024-pixel X-ray CCDs located at the focal plane of the telescope [see photo, p. 66]. The 10 CCDs are divided into a two-by-two array used for imaging and a one-by-six array used either for imaging or as a readout for diffraction gratings inserted between the Chandra telescope and the detector. There are two such gratings. Their job is to intercept X-rays reflected from the telescope's mirrors, changing the rays' direction in lock-step with the amount of energy they contain. One of the focal plane detectors records the location of the diffracted X-rays for precise determination of their energies. The spectrometer is good at this. It can distinguish up to 50 different levels of energy between 100 eV and 100 keV, corresponding to wavelengths from about 10 nm down to 0.01 nm.

Building large CCDs sensitive to X-rays was a challenge, said Barry Burke of the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, in Lexington, Mass. In the early 1990s, when the Chandra chip was designed, a million-pixel chip was large. Sensitivity to soft X-ray energies was needed in order to track down carbon. One of the most abundant elements in the cosmos, carbon has a key spectral line at 277 eV corresponding to a 4.5-nm wavelength.

X-ray CCDs differ from their visible-light counterparts in two key areas: higher substrate resistivity and thinner device layers. At photon energies below about 1 keV, the oxides and

CCD Primer

A charge-coupled device (CCD) is a semiconductor device that converts light into electronic bits of information. In essence, it is digital film.

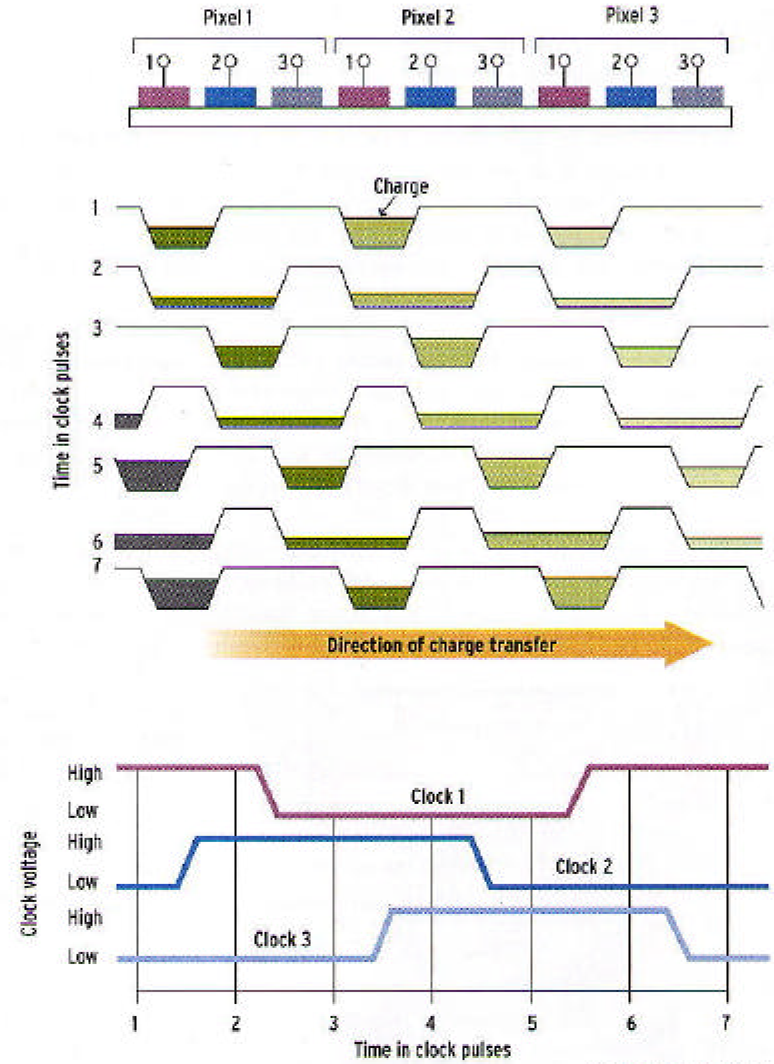
The CCD architecture has three basic functions: charge collection, charge transfer, and conversion of charge into a measurable voltage. Devices incorporating a CCD require an optical system to focus incoming light onto the CCD chip itself, which can range from millimeters to several centimeters across.

The basic building block of the CCD is the MOS capacitor, a metal electrode (gate) deposited on an oxidized substrate made of p-type silicon, meaning that the silicon has been doped with an impurity that is deficient in electrons. The resulting electron absence, or hole, drifts through the crystal, acting like a positive charge.

Consequently, a positive voltage applied to the metal electrode repels the holes (which in p-type silicon are the majority carriers) and forms a potential well at the silicon surface. This serves as one picture element (pixel), which is a square typically 10–20 µm across. If a photon of great enough energy is absorbed in the depletion region, it produces an electron-hole pair, which promptly splits up, with the electron moving toward the positive electrode and the hole moving toward ground. In this way the minority carriers (in this case, the electrons) accumulate at the oxide-semiconductor interface in an inversion layer about 10 nm thick.

MOS capacitors are created on a silicon wafer in arrays. Systematic and sequential manipulation of the individual gate voltages causes adjacent depletion regions to overlap, transferring the electrons from one gate to an adjacent gate in a conveyor-belt-like fashion. (The CCD was originally conceived as a shift register for computer memories.)

In one configuration, called a three-phase CCD, voltages on consecutive gates are controlled by three clock voltages that are out of phase with one another [see figure]. In the first stage, clock 1 is high and clocks 2 and 3 are low. So all the collected charge is held under the gates labeled **1**. In the second stage, clocks 1 and 2 are high and clock 3 is low, and the charge spreads out under gates 1 and 2. When clock 1 is brought low, the charge shifts to the region under gate 2. The result is that the collected charge has been shifted to the right by one gate. This process is repeated many times until each column of charge is transferred off the CCD and into an output amplifier. The columns of charge may be transferred and read one at a time. For faster applications, the entire frame of charges may be transferred to an almost identical array used for storage.



Source: Eastman Kodak

Since their invention over 30 years ago, CCDs have matured to where they are now widely affordable, and the centerpiece of many applications. They were first used in television cameras in 1975, to the relief of mobile cameramen's shoulders everywhere, and they also show up in flatbed scanners, camcorders, telescopes, industrial digital still cameras, machine vision cameras, optical character readers including bar code scanners, fax machines, and medical imaging equipment.

Soon after the CCD's invention, it was recognized that the interface between the silicon and the silicon oxide has traps and surface states that, though few in number, can affect the transfer of charge over long distances. So an extra layer of n-type semiconductor was implanted between the oxide and p-type silicon, distancing the active layer from the problematic interface. The resulting devices, called buried-channel charge-coupled devices (BCCDs), transfer charge faster and more completely.

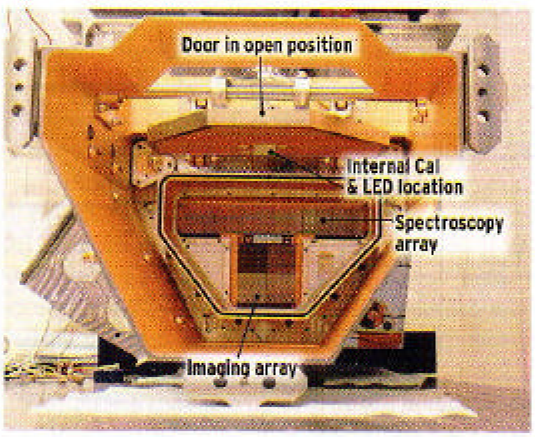
Finally, scientific-grade, slow-readout CCD cameras are often, these days, back-illuminated, in that the light arrives on the side other than the CCD's traditional front side. The payoff is that the image's photon enters the CCD unobstructed, and quantum efficiencies are high. The cost is that especially thin and expensive pieces of silicon are required. —D.A.

gate materials on the surface of a conventional CCD absorb very heavily. So designers of X-ray CCDs make these structures as thin as possible to reduce the number of X-rays absorbed before they can be detected. The X-rays that do make it through are collected in depletion regions under the gates. A high-resistivity substrate enables a deep depletion zone to collect the X-rays, which penetrate far into silicon. Ultimately, back-side illumination is utilized for very low energies.

Science revolutionized

CCDs are solid-state imaging chips jam-packed with metal-insulator-semiconductor capacitors that convert incident light into packets of electric charge [see "CCD Primer," p. 65]. "Every area of science has been revolutionized by the CCD, including every area of astronomy," said Tony Tyson, an astrophysicist at Bell Labs in Murray Hill, N.J.

Tyson (and, separately, Ed Lowe at Princeton University) was the first to install a CCD camera on a telescope. In 1979, at the Lowell Observatory in Flagstaff, Ariz., Tyson fitted its 1.8-meter-diameter telescope with a 4-by-4-mm^2 imager. In



Chandra's Advanced CCD Imaging Spectrometer has a two-by-two-CCD imaging array; a one-by-six spectroscopy array measures the X-rays' energies.

1980 he used it to study a quasar's host galaxy too faint to be studied with photographic plates.

CCD cameras have several technical advantages, foremost among them a high quantum efficiency. The term describes the percentage of photons incident on a sensor that are recorded. The best quantum efficiency available from photographic plates is about 5 percent, whereas initial CCDs already hit 50 percent or higher. (Current technology attains about 90 percent.)

Consistency is another CCD plus. Whereas every photographic plate has a unique set of deficiencies and is good for only one exposure, a CCD camera uses the same detector each time, whatever its shortcomings. Suppose it has a bad pixel. If pictures of an object are "dithered" by slightly changing the telescope's direction each time, an image that is free of the pixel defect can be built by mathematical transforms. This "shift and stare" technique, invented by Tyson, is now used with most space telescopes and can produce images from a telescope detecting about one photon a minute, such as might come from an object billions of light-years away.

Accuracy plus size

"The thing that CCDs have gotten for us," said Tyson, "that we could never achieve with photography or even television systems is very accurate photometry," the measurement of light intensity. Astronomers have been hard at work pushing this advantage to its extremes.

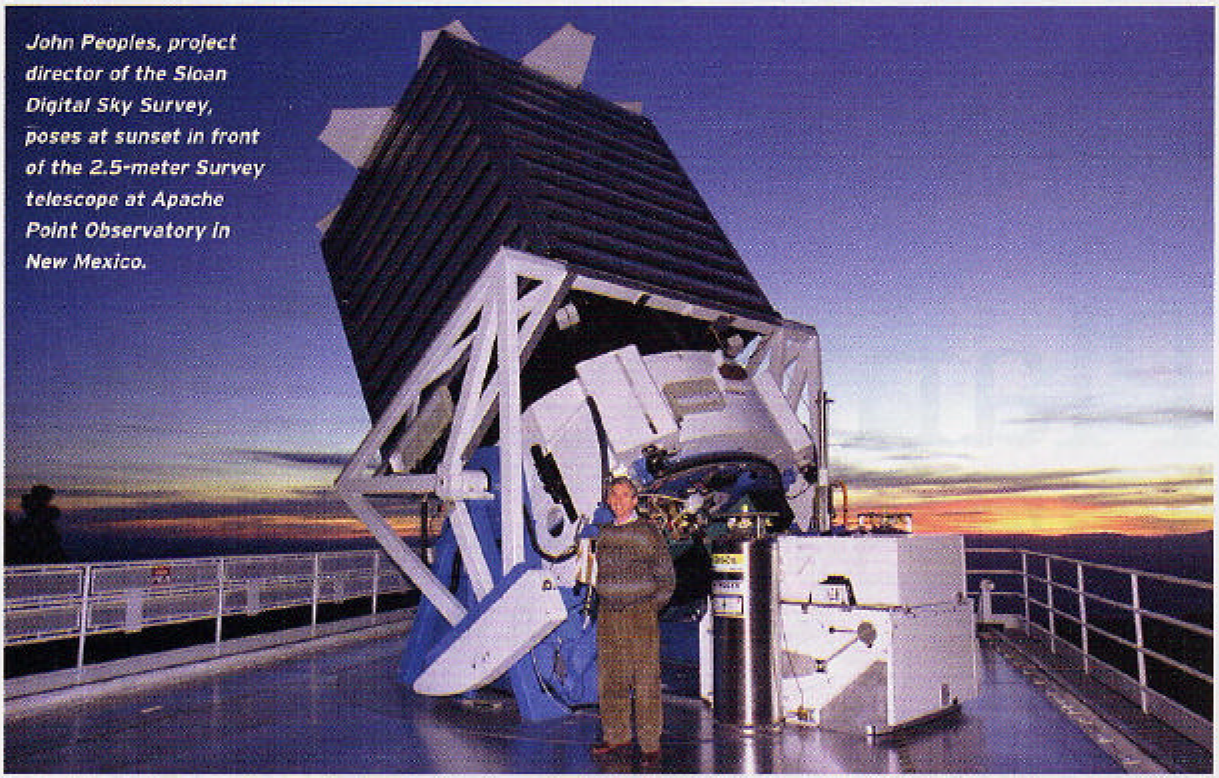
CCDs have grown in size from just millimeters to large arrays built from tens of individual CCD chips and akin to the 20-by-25-cm photographic plates once used in observatories. The largest is the CCD array at the photographic heart of the Sloan Digital Sky Survey (SDSS), a project being conducted on the 2.5-meter telescope at the Apache Point Observatory in New Mexico [see photo, right]. Here the visible and infrared parts of the spectrum are involved.

The Sloan survey's goal is to compile a virtual laboratory for astronomers—in essence, a detailed digital map of one-quarter of the entire sky—by determining the positions and absolute brightness of more than 100 million celestial objects. It has already discovered about a thousand quasars, one of which is the most distant object ever observed. These quasi-stellar radio sources are compact but luminous objects thought to be powered by black holes with masses a million times the mass of our sun. When the record-setting quasar emitted the light detected by SDSS, the universe was only about a billion years into its present 14-billion-year span.

The CCDs used for the telescope's camera were manufactured by Scientific Imaging Technologies Inc. (SITe), in Tigard, Ore. There are 30 CCDs in the camera, butted against one another in a five-by-six array. Each CCD consists of more than four million pixels, each pixel measuring 24 μm on a side, and the entire array has an effective imaging area of 720 cm^2. (Another array consisting of twenty-four 2048-by-400 CCDs is used for astrometrics, allowing SDSS researchers to match bright standard stars to celestial objects imaged by the photometric array.) The larger array uses filters to carry out photometry in five colors; at some wavelengths the quantum efficiency of the devices exceeds 80 percent. Pixel arrays this large generate an immense amount of data—up to 200 GB from one night's observation.

Suprime-Cam, the Subaru Prime Focus Camera from Japan, is a wide-field camera consisting of two rows of five CCD chips. As each has 2048 by 4096 pixels, the array totals over 80 million pixels. That's about 10 times as many as in a photograph from a very good 35 mm camera and 40 times as many as in a high-end digital camera. The array sits at the focal point of the 8.2-meter Subaru Telescope on the summit of Mauna Kea, in Hawaii, and covers wavelengths of 300 to 1100 nm. Since its first light two years ago or so, the Suprime-Cam and Subaru, a subsidiary of Tokyo Subaru Motors Co. in Tokyo, have detected some of the faintest galaxies ever to have been observed.

In the works could be the first billion-pixel camera. The hope is that it will uncover what MIT physicist Frank Wilczek



John Peoples, project director of the Sloan Digital Sky Survey, poses at sunset in front of the 2.5-meter Survey telescope at Apache Point Observatory in New Mexico.

DAN LONG/ APACHE POINT OBSERVATORY

called "maybe the most fundamentally mysterious thing in basic science—dark energy." The SuperNova/Acceleration Probe (SNAP) satellite has been proposed by Lawrence Berkeley Laboratory scientists and others. It would consist of a roughly circular CCD array over a third of a meter wide, with a one-square-degree field of view and quantum efficiency greater than 80 percent. Proposed as part of it is a mirror 200 cm in diameter, or only about 16 percent smaller than the Hubble Space Telescope. The mirror and camera are to map over 6000 distant supernovae.

The project could launch as early as 2008. Among the questions about the expansion of the universe it may answer is the puzzling 1998 discovery that the rate of the expansion is accelerating due, apparently, to the mysterious "dark energy" that accounts for as much as two-thirds of the energy density of the universe.

The best is yet to come

"CCDs have been riding the coattails of the boom in integrated chip design," said Burke of MIT Lincoln Laboratory, "[delivering] sensors that do science we couldn't have done 10 or 20 years ago." According to Burke, the CCD designers now confront the need not just to build larger chips but also to further improve quantum efficiencies and reduce noise in the charge-detection circuitry at the CCD's output. While a consumer CCD may have dozens of electrons' worth of noise, the Chandra CCDs have just one or two electrons' worth.

Increasing yield is also a priority. The yield is the percentage of chips on a wafer that function at a specified performance level. For very large chips this figure can fall as low as 10 percent, but these are the chips that are most desired by astronomers. Scientific CCD designers like those at MIT Lincoln Laboratory must find a balance between yield and chip size (smaller chips require more supporting electronics) that works well and gives a good supply of devices for the astronomy community.

The annual world market for CCDs is about US $1 billion, mostly in digital still cameras and other consumer applications, with scientific CCDs forming a specialized market of about $100 million a year. Clearly, the charge-coupled device is a technology that has fully arrived, threatened only by potential intruders like the CMOS image sensor. CMOS sensors are built on silicon chips, as are CCDs, but, unlike CCDs, have active pixels: that is, the supporting circuitry for the device is located right beside each light receptor.

CMOS chips have carved out about 10 percent of the digital imaging market, mostly in consumer applications. But penetrating the scientific CCD market will be harder.

"CMOS could be another revolution for astronomers," said Jim Janesick, an engineer who studies CMOS sensor performance at semiconductor supplier Conexant Inc., in Newport Beach, Calif. "The main problem is, how do you swing CMOS toward scientific sensors?" he said. He noted that today CMOS wafer production is only for customers who desire several hundred large wafers a week, even if performance suffers a bit.

Janesick believes it will be about five years before CMOS sensors are in a position to threaten scientific CCDs, but that success will require the attention of and input from the scientific community. "The commercial market is demanding, but not like the scientific community," he said. "Barbi-cam cameras aren't as demanding as Keck cameras." ●

Linda Geppert, *Editor*